(12) UK Patent Application (19) GB (11) 2 106 190 A

(21) Application No 8123574
(22) Date of filing 31 Jul 1981
(43) Application published
7 Apr 1983
(51) INT CL³
F03G 7/06
(52) Domestic classification
F1S 26
A6M 8F 8G
G1D 10X2 10X3 11
U1S 1170 3064 F1S
(56) Documents cited
GB 1573204
GB 1549166
GB 1544075
GB 1539637
(58) Field of search
F1S
G1D
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(54) Thermally responsive actuators utilising shape memory, and exercising devices utilising the same

(57) The actuator comprises an elongate element 1, for example in the form of a twisted wire strand, of a shape memory alloy. The element 1 is provided with an elongate, flexible sleeve 2 in the form of a plastic tube. Permeable stops 7 may be provided to restrict axial movement of the element 1. Fluid can be passed through the tube 2 by means of an inlet 3 and an outlet 4. By varying the temperature of the fluid, the shape of the element 1 can be varied and in one preferred arrangement it changes between straight and curved states. Exercising devices for example for human limbs are also disclosed, these using the actuators together with a suitable supply of fluid. By alternating between hot and cold fluids, the devices can be made to move e.g. joints cyclically.

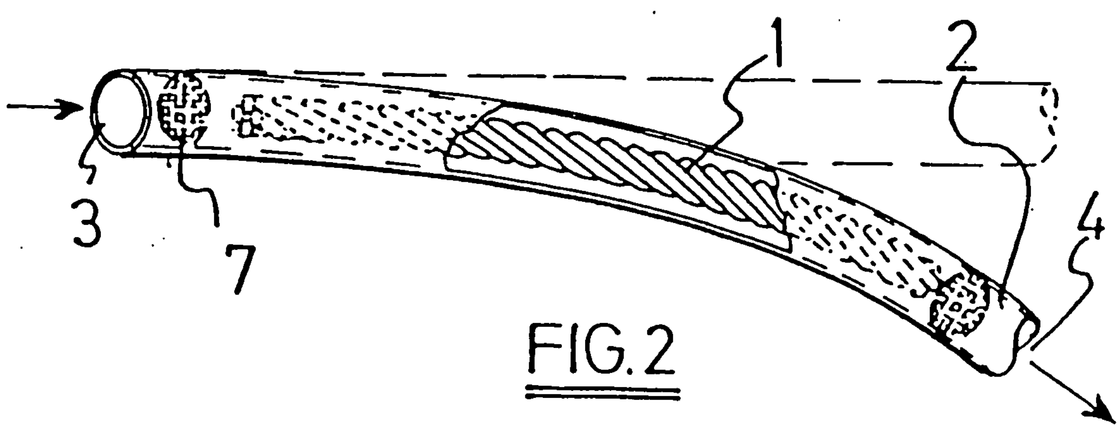

FIG.2

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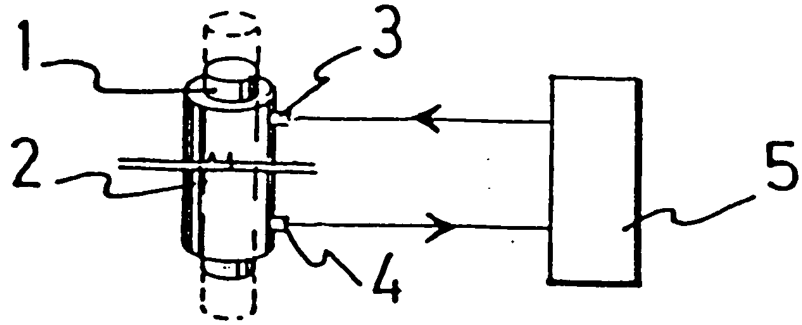

FIG.1

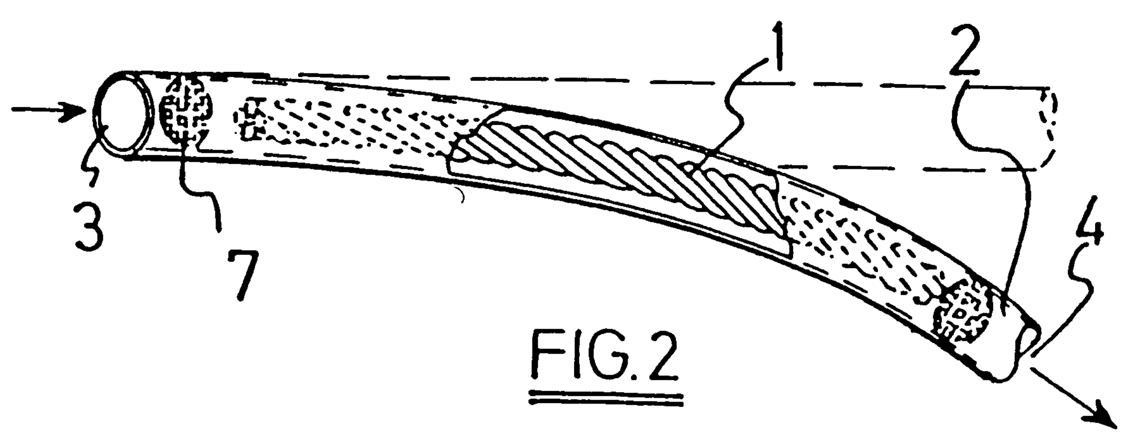

FIG.2

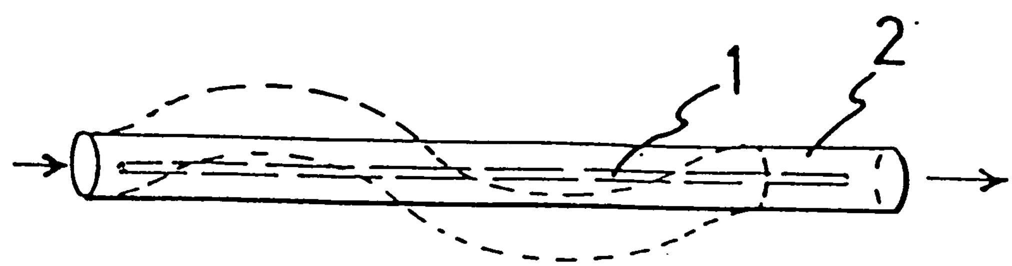

FIG.3

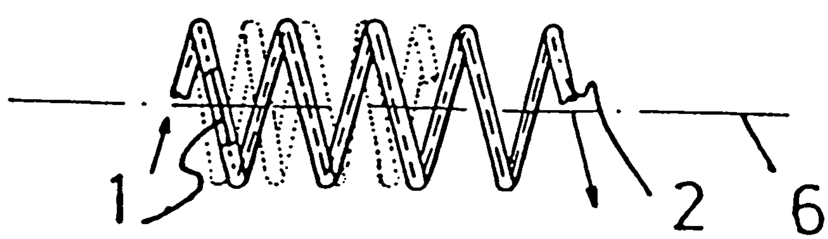

FIG.4

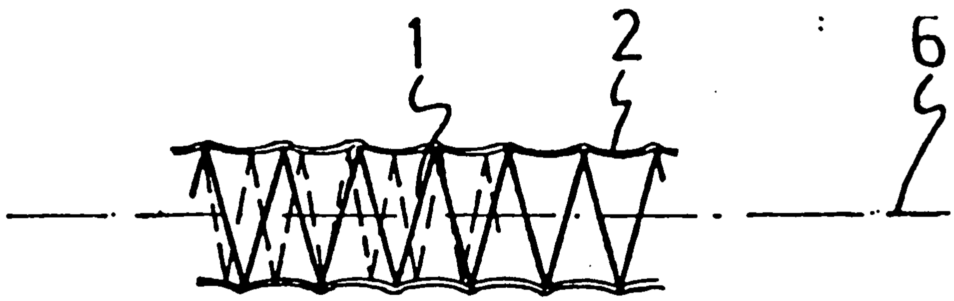

FIG.5

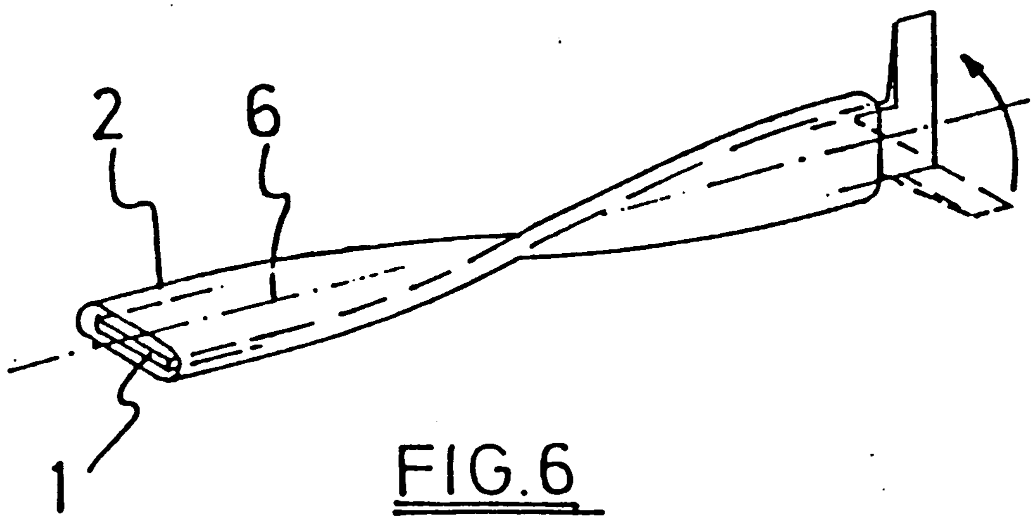

FIG.6

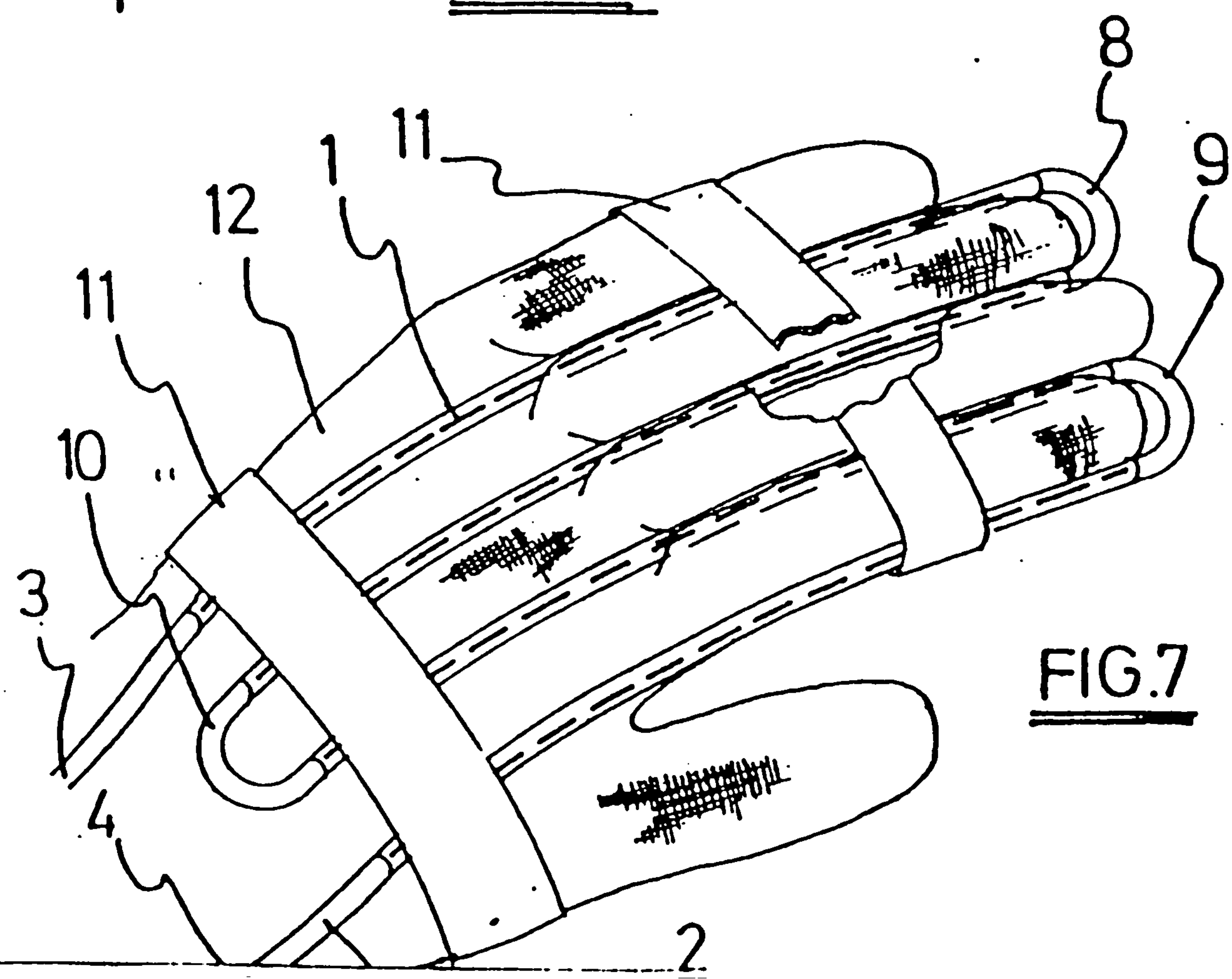

FIG.7

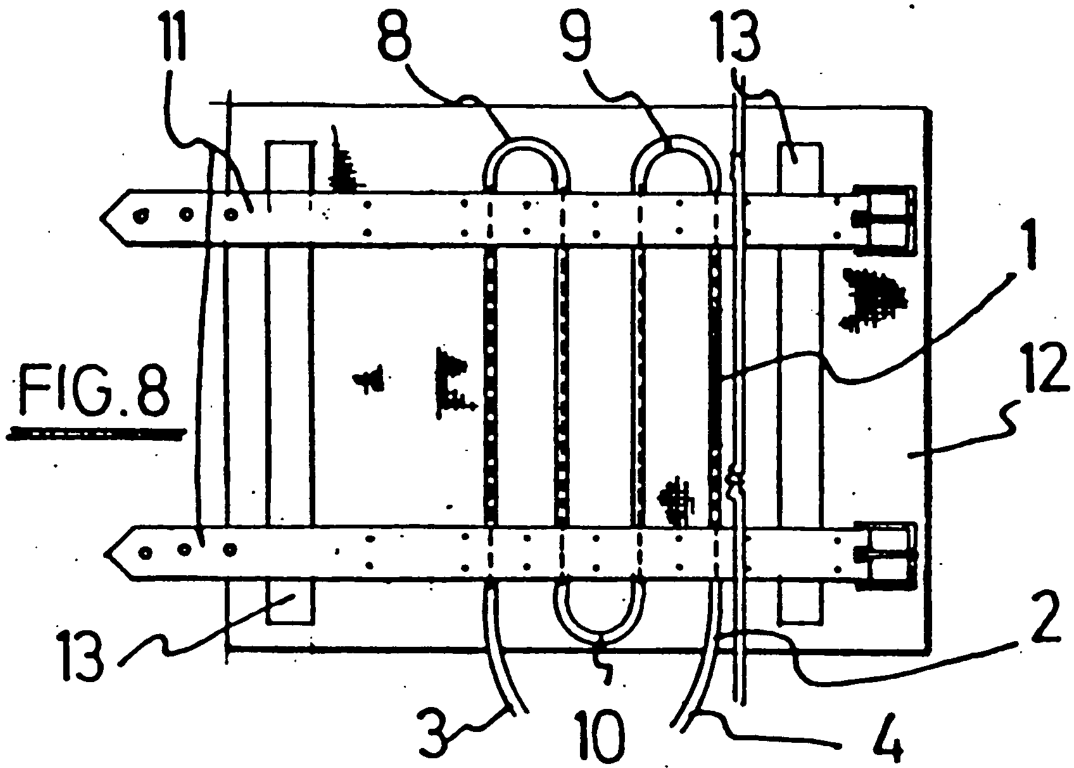

FIG.8

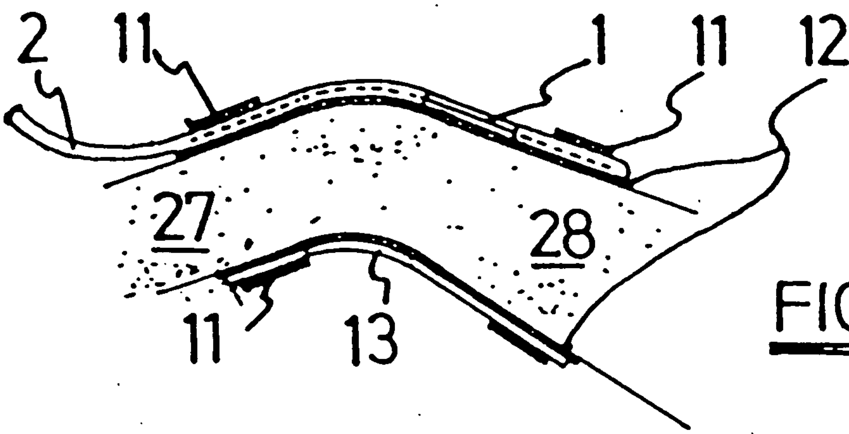

FIG.9

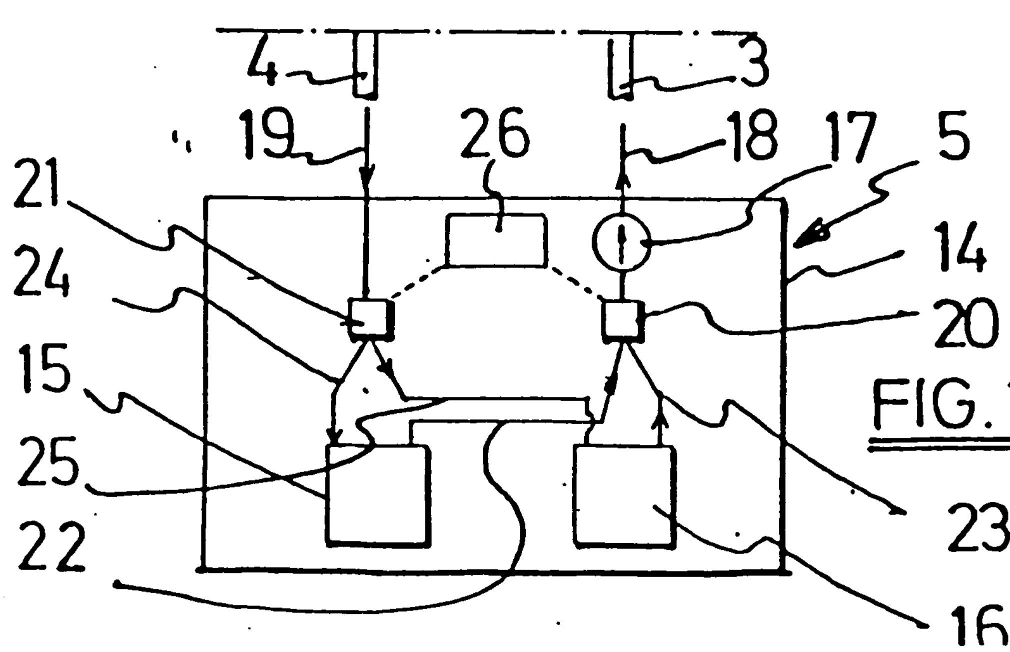

FIG.10

SPECIFICATION

Thermally responsive actuators utilising shape memory, and exercising devices utilising the same

The present invention relates to thermally responsive actuators utilising shape memory, and to exercising devices using such actuators for use in exercising e.g. human limbs.

The shape memory effect is exhibited by various materials and consists essentially in that an element of such a material when formed to an initial shape and subsequently plastically deformed to another shape at an appropriate temperature, will automatically revert at least to a substantial extent to its initial shape at a different temperature or tend to do so depending on the degree of outside restraint to which the element is subjected. Thus, such elements, in their deformed shape, can be subjected to heating and cooling through a transformation temperature range characteristics of the material, so as to cause a displacement towards their initial shape or tend to cause such a displacement and thus effect merely the exertion of a force on another member. The change can be made automatically reversible in relation to temperature changes.

The shape memory effect is particularly exhibited by certain alloys with a predominantly β phase composition which experience a transformation from austenite at a relatively high temperature to martensite at a relatively low temperature, and the reverse transformation at a higher temperature. Such alloys include alloys of Ni-Ti, In-Tl, Au-Cd, Ag-Zn, and $(Ni_{1-x}Cu_x)$-Ti. Particularly preferable alloys are of Cu with one or more of e.g. Zn, Al, Ni, Mn, Sn or Co. As disclosed in Dutch Patent Application 77.14494, powder metallurgical alloys are preferred because of their very homgeneous composition, finer grain composition, finer grain structure, and hence better fatigue resistance. The alloys can be formed by known metal preparation and shaping techniques into e.g. sheet, strips, rods, profiles or wires.

In general, an element of such an alloy is either formed into its "remembered" shape above the austenite transformation temperature A_f, or after forming at a lower temperature is heated to above the temperature A_f. The element is then quenched to a temperature below the martensite transition temperature M_f, and deformed plastically whilst in its martensitic state. If the element is subsequently heated to the austenitic phase, it reverts to its remembered shape. It will be appreciated of course that the phase transformations take place over ranges of temperatures — M_s to M_f, and A_s to A_f — and that the martensitic transformation can be stress induced at least in part.

Providing the temperature to which the deformed elements is heated is not too high, i.e. not excessively above A_f, then on subsequent cooling to the martensitic phase the element can change back again from its remembered shape to its deformed shape. This may require initial training, i.e. repeated heat treatment by alternating from below M_f to above A_f and mechanical deformation, before the reverse change in shape becomes spontaneous.

It has been proposed to use such elements in actuators for a variety of purposes. A problem with such actuators has been providing means for controllably heating and cooling them cyclically in a simple and rapid manner without requiring cumbersome heating and cooling arrangements.

In accordance with the invention there is provided a thermally responsive actuator comprising an elongate element with shape memory, there being a passage extending along the element, and means for passing a heating and/or cooling fluid through the passage to effect or tend to effect a change in shape of the element by means of a shape memory effect, the passage being capable of movement with the element should such a change in shape thereof occur.

The passage could be defined for example by a bore through the shape memory element itself which could be in the form of a tube. Preferably, however, the passage is defined by a flexible sleeve for the shape memory element, such as a hose or tube.

Thus, the shape of the element can be controlled simply and quickly in accordance with the temperature of the fluid flowing through the sleeve; alternatively, if the element is restrained, the force exerted by it on the restraining member can be varied. With a suitable element these effects can be achieved cyclically by alternating between a hotter fluid and a cooler fluid. The fluid may be a gas, liquid, or a mixture thereof. Depending for example on the temperature differences involved if both heating and cooling are required, the heating and cooling fluids may be the same or different.

Means such as one or more pumps will generally be provided for circulating the fluid, as well as means for controlling the temperature of the fluid.

Means may be provided for connecting the actuator to a member to be actuated.

The shape memory element can be in the form of e.g. a wire, a bundle of wires, twisted strand or cord, a small diameter tube, a strip, a rod, or a profile. The element can be generally linear in form, or e.g. in an undulating or spiral configuration.

The shape memory element can extend over the whole or part of the length of the sleeve, or may even extend beyond the sleeve — suitable sealing means being provided at the points of entry and/or leaving the sleeve. For certain applications it is desirable to have a plurality of elements which act together or which are arranged to produce different effects — i.e. different shape changes, different temperature responses, or the like. Thus, for example, a first strip element in a first portion of a sleeve could produce bending whereas a second helicoidal spring wire element could produce a change in

axial length at another temperature in another portion of the sleeve. The plurality of elements can be in a single continuous sleeve or in a series of sleeve portions joined together. The shape memory element may be acted on by a member providing a returning force, such as a biasing spring — e.g. a leaf spring or a helicoidal spring. The element could be appropriately connected by suitable means to, or in temporary contact with, such a member. The degree of displacement will depend not only on temperature but on the strength of the returning force.

The biasing spring could be made from a material with pseudoelastic properties. Alloys having the composition of shape memory alloys with the capability of martensite formation under stress, exhibit normal elastic behaviour under stress until the critical stress is reached at which martensite plates begin to form. With further stress, deformation appears to be plastic, but once the stress is removed the martensite transforms and the element concerned reverts to its original shape with no permanent deformation. This behaviour is termed "pseudoelastic". An advantage of e.g. pseudoelastic wires is that they have better bending fatigue properties than spring steel wires, especially when bending strains or more than 2g are imposed.

It will be appreciated that if a pseudoelastic element is to be used as a biasing spring over the temperature range of operation of a shape memory element, then its M_s temperature in the unstressed state should be below that of the shape memory element, or there may be temperature rather than stress transformation of the biasing spring and it may not revert to its austenitic form.

In general, where a restoring force is required, it may be advantageous to use elements of a similar alloy but slightly different compositions and thus with different M_s temperatures so that one exhibits the shape memory effect, and one the pseudoelastic effect. The two types of element could be in the same sleeve. Alternatively the psuedoelastic elements could be arranged along the outside of the sleeve.

Actuators in accordance with the invention are particularly in use in the medical field, i.e. in devices for exercising body parts such as human or even animal limbs, joints or muscles. Such a device can be used to reactivate or stimulate the movability of, or the development of forces in, such body parts. The device may comprise a supporting member to be fixed by suitable means on the body parts to be treated, the member carrying one or more actuators according to the invention with the or each shape memory element suitably disposed or oriented so as to provide exercising — i.e. flexing — in the direction required, in response to controlled temperature changes. The or each actuator could alternatively be mounted directly on the body part.

Some embodiments of the invention will now be described by way of example and with reference to the accompanying drawings, in which:—

Figure 1 is a view of a first embodiment of an actuator in accordance with the invention;

Figure 2 is a view of a second embodiment of an actuator in accordance with the invention;

Figure 3 is a view of a third embodiment of an actuator in accordance with the invention;

Figure 4 is a view of a fourth embodiment of an actuator in accordance with the invention;

Figure 5 is a view of a fifth embodiment of an actuator in accordance with the invention;

Figure 6 is a view of a sixth embodiment of an actuator in accordance with the invention;

Figure 7 is a view of an exercising glove utilising an actuator in accordance with the invention;

Figure 8 is a view of an exercising belt for joints utilising an actuator in accordance with the invention;

Figure 9 is a view of the belt of Figure 8 in position on a joint; and

Figure 10 is a schematic view of apparatus for controlling the flow and temperature of fluid in actuators in accordance with the invention.

Referring now to Figure 1, there is shown an actuator comprising a rod like member or pin 1 of a shape memory alloy, constituting a temperature responsive element to be alternatively heated or cooled whereby the length of the pin changes, i.e. increases or decreases as desired, upon being subjected to the different temperatures. Heating and cooling are carried out by alternately circulating a fluid at the appropriate temperature through a flexible sleeve in the form of a tube or hose 2 with inlet 3 and outlet 4. Heating or cooling means, a circulating pump for the fluid and means for switching from a higher temperature to a colder can be arranged as desired, and as illustrated they can be arranged in a feeding apparatus 5 connected to inlet 3 and outlet 4. The speed of heating and cooling is of course dependent inter-alia on the contact area between the element and the heat exchanging fluid and on the output of the circulating fluid. To improve the heat exchange efficiency, the pin 1 can thus have e.g. a T-shaped or tubular cross section instead of a circular one. Means may be provided to avoid uncontrolled displacement of the pin in the tube.

Figure 2 shows an actuator comprising a flexible tube 2 with inlet 3 and outlet 4 in which a shape memory element 1 is located being in the form of a twisted wire bundle or strand. The wire strand of the appropriate alloy composition can be conditioned by a suitable pre-treatment to produce a desired bending deformation thereof in response to temperature changes, the element bending e.g. to the dotted line position shown. As the tube is flexible, it can easily follow the formation induced in the element. Fluid pervious stops 7 of e.g. fine wire gauze can be inserted in the tube ends to prevent axial sliding of the element 1.

An important advantage of using wire bundles, e.g. twisted cords, relates to the fact that a smaller bending radius is possible. This is because the

allowable bending deformation, which is generally less than 2% and preferably less than 1%, depends upon the wire diameter and not the bundle diameter. The bending deformation percentage is defined by the ratio of the wire diameter to two times the radius of curvature of the bend.

Another actuator is illustrated in Figure 3, where there is shown a flexible tube 2 contacting a wire-like shape memory element 1 which has been heat treated and conditioned to change from a straight to a wavy-like shape shown by dotted line in response to temperature changes. In Figure 4, there is shown an actuator comprising a shape memory element in the form of a helicoidal spring 1 sheathed with a flexible tube 2 and arranged for contraction and expansion along its axis 6 as indicated by dotted lines. In the alternative arrangement of Figure 5 the entire coil spring 1 can be inserted in a flexible tube tho longitudinal axis thereof being parallel to the axis 6 of the coil. The radial outer portions of the coil convolutions of spring 1 contact the inner wall of the flexible tube 2 and axial contraction or expansion of the spring 1 will be transmitted to the contacting wall of tube 2.

In the embodiment of Figure 6 the actuator comprises a strip 1 of shape memory material. The deformation induced can then result e.g. in a change of shape by twisting around the longitudinal axis 6 of the strip in the direction of the arrow shown, or the reverse direction when alternatively a warmer and a colder fluid are circulated in a sleeve 2 surrounding the strip.

In Figure 7 there is shown an exercising device consisting of a dynamic hand splint. This is in the form of a glove 12 as a supporting sheet to whose back a tube 2 is attached in a wavy shape so that two wave crests 8, 9 are situated next to the finger tips, whereas an intermediate wave trough 10 is situated next to the wrist. Four elements 1 of shape memory alloy extend in the tube portions substantially parallel to the fingers respectively between tube inlet 3 and wave crest 8, trough 10 and crests 8 and 9, and tube outlet 4 and crest 9. A single convoluted element could be used. Binding straps 11 are provided to press the parallel tube portions with a glove against the hand.

The tube 2 is formed of P.V.C. and comprises four parallel portions of internal diameter 6 mm connected by three curved P.V.C. tube portions at crests 8, 9 and trough 10, and provided with P.V.C. inlet and outlet portions. A single continuous, convoluted sleeve could be used.

In each of the substantially parallel tube sections the element 1 consists of a bundle of seven wires each having a diameter of 1.8 mm. The wires are made from a shape memory alloy including an appropriate content of Cu, Zn, Al having a predominant β-phase composition and M_s temperature of about 10°C in an unstressed condition. The wire bundles have been preconditioned by heating to about 700°C whilst being kept substantially straight to ensure that the entire material is in the β-phase condition, and subsequently quenched. They were then trained by heat treatment and deformation so as to be straight in the austenitic (high temperature) state, and bent with a radius of curvature of 50 mm, in the martensitic (low temperature) state. Each of the tube sections is provided at both ends with metallic filters. The tube sections are attached to the glove back and suitable binding straps 11 are applied.

The hose inlet and outlet portions 3 and 4 are connectible to alternative sources of water at respective temperatures of about 5°C to 10°C and about 70°C. A pump is provided to circulate the water with an output of approximately 1.2 l/min through the system at a pressure of about 2 atmospheres. When circulating the hot water at about 70°C through the tube, the wires change from the curved to the straight shape and thus urge the fingers — which were contracted by spasm in a flexed position — with an acceptable force and speed into their extended or straight position. When desired subsequently, the cold water at about 10°C is circulated through the tube whereupon the straightening forces disappears in the wires and the fingers can be easily flexed by their normal action, so bending the wires. The cycling frequency of cold and hot water can of course be adapted to the intensity of the desired rehabilitation exercising or training desired. By adjusting the temperature of the hot water (which must be above A_s for the alloy of the elements) the straightening force and speed of shape change can be controlled so as to avoid exaggerated pain for the patient.

The dynamic hand splint described above is intended to be used mainly for rehabilitation following two kinds of diseases namely spasm of the hand in an extended or flexed situation and inability to move the hands e.g. with patients in coma.

In the first case the lacking activity of muscles can be reactivated by alternately imposing extension and a flexing movement to the fingers to regain the normal function of the paralysed hand and/or to prevent its further disfigurement. Previously used splints are only capable of applying static changes in shape, i.e. the hand is forced by the splint in a certain position and kept so for a certain period of time after which the splint is removed. The system described above however allows a dynamic exercising of the hand. Further when connected to a monitoring unit, to circulate the hot and colder fluid through the tube at desireable time intervals, the extension and flexion movements can automatically be applied.

The exercising glove above described also offers the psychological advantage for patients that its appearance is less mechanised than that of the usual hand splints. The appearance can be made even more attractive by covering the glove and the attached actuator with another mitten i.e. fingerless gloves, so as to dispel a patient's general dislike for medical devices which look complicated.

Another example of a device for exercising body

parts relates to an exercising belt for joints as shown in Figures 8 and 9. Thus, a tube 2 is attached in a wavy shape onto a support in the form of a belt 12 in the same manner as for the glove described above. The substantially rectilinear tube portions containing actuating elements 1 of shape memory alloy, or a single convoluted element, are oriented substantially parallel to the direction of limb extremities 27, 28 which meet each other at a joint, and are mutually connected by means of curved tube portions 8, 9 and 10 as before. Fixing means such as binding straps 11 are provided to press the belt against the limb extremities 27 and 28.

The operation of the device corresponds to that of the glove described above. In the case of patients incapable of moving some of their joints it will generally be desirable to exercise these joints to avoid later joint stiffness. However there the presence of members capable of exerting a returning force against the actuating elements will be necessary. Such members 13 are shown in Figures 8 and 9 and may comprise any strip material with appropriate elastic bending behaviour. Such a strip material may consist e.g. of a Cu-Zn-Al alloy with pseudoelastic properties and be attached to the sheet 12 in a parallel relationship to the elements.

Similar members exerting the desired return bending force could of course be arranged in the palm side of the glove described above, parallel to the fingers. In one possible arrangement the actuating element for the glove could be shape memory wires with an M_s of $-10°C$, and biasing springs similar but with an M_s of $-30°C$ so as to behave pseudoelastically.

In Figure 10 there is shown schematically, a suitable monitoring system 5 for supplying fluid to the actuators in accordance with the invention. This apparatus comprises a frame 14 with a thermostatically controlled reservoir 15 for the fluid at a lower temperature, and a thermostatically controlled reservoir 16 for the fluid at a higher temperature. A fluid pump 17 with controllable output is arranged on the frame for delivering fluid at the desired temperature through supply conduit 18 to the connected inlet portion 3 of hose 2 and pumping alternatively fluid from reservoirs 15 and 16 and returning it to the same reservoir after circulation through hose 2 whose outlet 4 is connected to the return duct 19 of the system. Switching devices in the form of solenoid valves 20 and 21 are respectively arranged between pumps 17 and fluid supply ducts 22, 23 and reservoirs 15 and 16 and between return duct 19 and return branches 24, 25 for the reservoirs 15 and 16.

The switching devices are controlled to produce the circulation flow direction as indicated by the arrows on the different duct portions. The signals for operating the switches to alternate the fluids properly are given by a conventional timing unit 26. The command signal in unit 26 for switching valve 20 to circulate fluid at a new temperature runs in advance to that for valve 21 for a time sufficient to circulate residual fluid at the first temperature through hose 2, ducts 19 and 24 or 25 to the appropriate reservoir as the case may be. In this way undue mixing of warmer and colder fluid in the reservoirs is largely prevented.

It will be noted that by using actuators in which the shape memory elements are provided with a flexible sleeve, such as a tube or hose of P.V.C. or any other suitable rubber or plastics material, good thermal control can be provided and the sleeve can move with the elements so as to maintain such control. This will of course occur in any event if the memory element is in the form of a tube through which the fluid passes. A helicoidal shape memory tube could be used in place of the embodiment of Fig. 4, and a flattened tube in place of the embodiment of Fig. 6.

CLAIMS

1. A thermally responsive actuator comprising an elongate element with shape memory, there being a passage extending along the element and means for passing a heating and/or cooling fluid through the passage to effect or tend to effect a change in shape of the element by means of a shape memory effect, the passage being capable of movement with the element should such a change in shape thereof occur.

2. An actuator as claimed in claim 1 wherein the shape memory element is of an alloy exhibiting a reversible temperature dependent martensitic transformation.

3. An actuator as claimed in claim 2 wherein the element is of an alloy including Cu, Zn and Al.

4. An actuator as claimed in claim 3 wherein the alloy further contains one or more of Ni, Mn or Co.

5. An actuator as claimed in claim 2 wherein the element is of an alloy including Ni and Ti.

6. An actuator as claimed in any preceding claim, wherein the passage is defined by an elongate flexible sleeve for the shape memory element.

7. An actuator as claimed in claim 6 wherein the sleeve is in the form of a tube of rubber or plastics material.

8. An actuator as claimed in claim 6 or 7 wherein the element is in the form of a bundle of wires or a strand or cord of twisted wires.

9. An actuator as claimed in claim 6 or 7 wherein the element is in the form of a wire.

10. An actuator as claimed in claim 6 or 7 wherein the element is in the form of a strip.

11. An actuator as claimed in any of claims 6 to 10 wherein a biasing element is provided for exerting a return force on the shape memory element.

12. An actuator as claimed in claim 11, wherein the biasing element is an elongate pseudoelastic element.

13. An actuator as claimed in claim 12 wherein the pseudoelastic element is positioned within the sleeve.

14. An actuator as claimed in claim 12 wherein the pseudoelastic element is attached to the

outside of the sleeve.

15. An actuator as claimed in any of claims 6 to 14 wherein a plurality of shape memory elements exhibiting different temperature dependent shape change characteristics are provided in a common sleeve or a series of sleeves connected together.

16. An actuator as claimed in any of claims 1 to 5, wherein the passage extends through the shape memory element.

17. A device for exercising a part of a body, comprising at least one actuator as claimed in any preceding claim and means for attaching the or each actuator to the body part with the or each shape memory element having a predetermined orientation relative thereto.

18. A device as claimed in claim 17 in the form of a glove having a plurality of shape memory elements, or a convoluted single element, arranged to provide a generally parallel array extending longitudinally from the wrist region to the fingertip region.

19. A device as claimed in claim 18 wherein the palm of the glove is provided with a member for exerting a return force against force exerted by the or each shape memory element.

20. A device as claimed in claim 17 in the form of a belt for attachment to a limb in the region of a joint, comprising a sheet having mounted thereon a plurality of shape memory elements, or a convoluted single element, arranged to provide a generally parallel array extending longitudinally in the direction of the limb.

21. A device as claimed in claim 20 wherein there is mounted on the sheet a member for exerting a return force against the force exerted by the or each shape memory element.

22. A device as claimed in any of claims 18 to 21 wherein the shape memory elements, or the portions of the single convoluted element, constituting the parallel array are arranged in series within a single continuous flexible sleeve or a plurality of flexible sleeve portions joined in series, defining the or each passage through which the heating and/or cooling fluid can be passed.

23. An actuator, or an exercising device, as claimed in any preceding claim wherein the or each passage is connected to means for supplying fluid at two different temperatures and means are provided for selecting at which of said temperatures fluid is circulated and for changing between said temperatures so as to effect or tend to effect a shape memory effect in the or each shape memory element.

24. A thermally responsive actuator, substantially as hereinbefore described with reference to Figure 1; or Figure 2; or Figure 3; or Figure 4; or Figure 5; or Figure 6 of the accompanying drawings.

25. An exercising glove substantially as hereinbefore described with reference to Figure 7 of the accompanying drawings.

26. An exercising belt substantially as hereinbefore described with reference to Figures 8 and 9 of the accompanying drawings.

27. An actuator, glove or belt as claimed respectively in claims 24, 25 or 26 in combination with a fluid supply system substantially as hereinbefore described with reference to Figure 10 of the accompanying drawings.

Printed for Her Majesty's Stationery Office by the Courier Press, Leamington Spa, 1983. Published by the Patent Office 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.